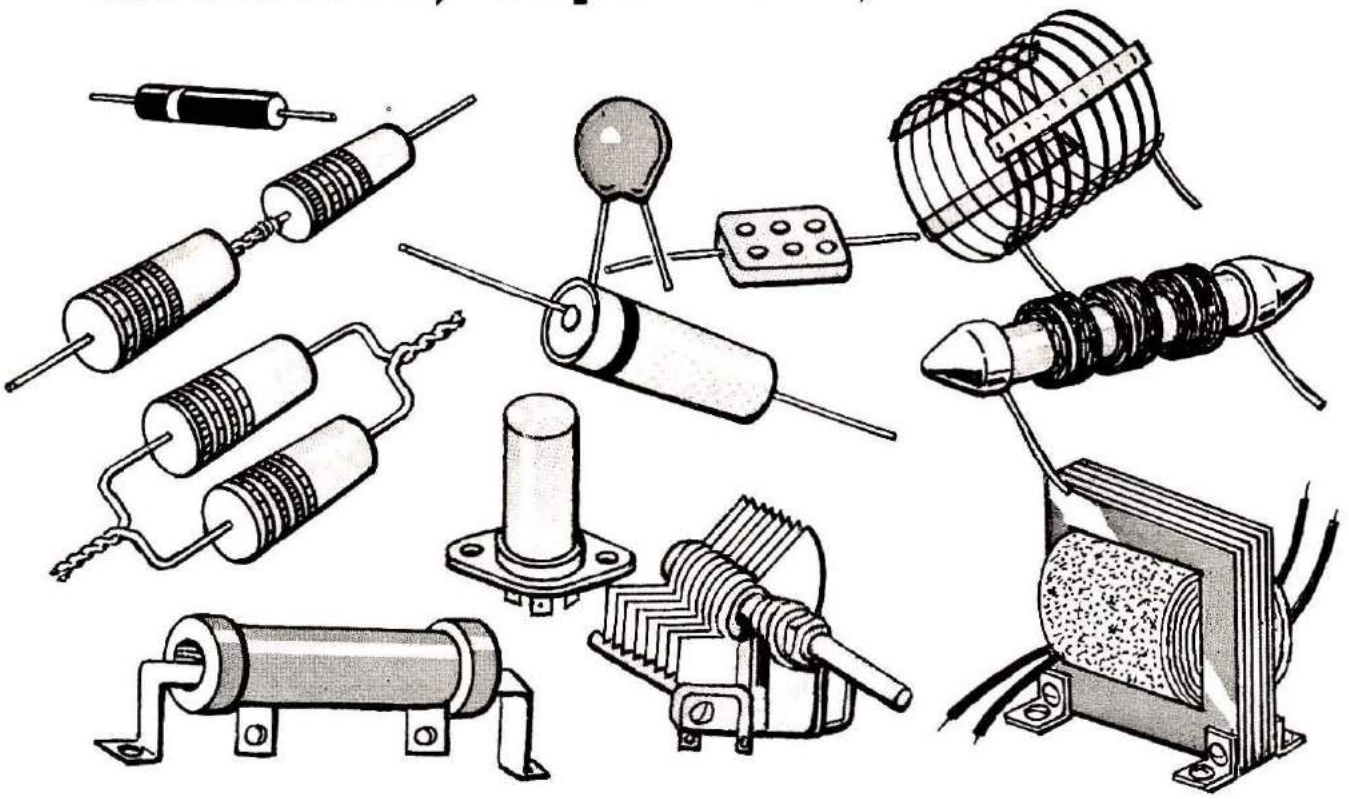
Understanding
Resistors, Capacitors, & Inductors



Some basic principles behind three of the most common electronic components

BY PAUL G. SCHREIER, WA1TWT

If you're just starting to study electronics you've probably been overwhelmed by the huge number of new devices and concepts. Although this collection of unfamiliar ideas may appear bewildering, if each is analyzed separately you'll be surprised how easy electronic theory can be.

Almost every electronic circuit uses three basic elements: *resistors, capacitors,*and *inductors*. Let's get acquainted with them and see how they behave in electronic circuits.

Resistors slow down everything

Probably the most common component in all electronic circuits, resistors do nothing more than agree with their name — they "resist" and limit the flow of electrons in a circuit. You can tell how much a device resists current flow by looking at its resistance value, measured in *ohms* (and represented by the Greek symbol Ω).

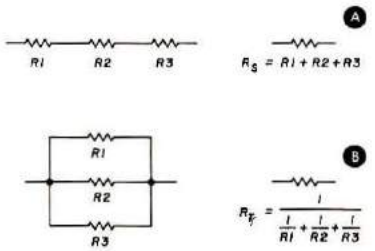


Fig. 1. With series resistors, **A**, electrons must pass through each resistor; sum their values to find the equivalent resistance. For the parallel case, **B**, however, electrons are split among the possible paths.

Also note that even conductors — wires or other paths designed to carry current — have resistance, although these values are very small, and you'll generally ignore such effects when working with circuits. But every resistor operates *linearly*. This means that, no matter how much voltage you apply across a resistor, the resistor passes only a certain current, I, with a value represented by

$$I = \frac{volts}{resistance}$$

Linearity also means that if you double the voltage, you double the current, so that a resistor's value remains *constant* under any condition, no matter if you apply ac or dc

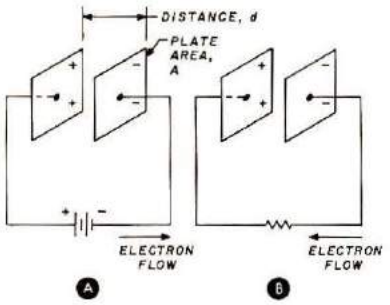


Fig. 2. Capacitors charge when a source pushes electrons into one plate, leaving an absence of electrons (or *holes*, indicated by + signs) in the other plate, **A**. If given the opportunity, however, the charged particles will return to equilibrium; you can encourage that by removing the source holding the electrons on the plate and providing a return path, **B**.

power. Resistors pass all frequencies with equal ease.

What would you expect if you hindered current flow once with one resistor and then did the same thing immediately afterwards with another resistor? **Fig. 1A** shows that you can add these *series* resistances directly:

$$R_S = R1 + R2 + R3 + \ldots$$

where

$R_S = R_{sum}$ of the resistors **(1)**
$R1 \ldots R2 \ldots$ = Resistance of each element (ohms)

For instance, suppose you needed a 1 kilohm (1000 ohm) resistor, but you have only smaller values? Just connect two 500-ohm resistors in series — it's as simple as that.

Parallel resistors **(Fig. 1B)** are a bit more tricky. Instead of making it more difficult for current to flow, the additional resistors offer more paths for the current to take and thus reduce the *effective* total resistance. You can calculate parallel resistance with this formula:

$$R_T = \frac{1}{\frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} + \ldots} \quad \textbf{(2)}$$

where

R_T = Total resistance (ohms)

Again, using those two 500-ohm resistors, wire them in parallel. This time you have the effective value of each resistor and get $R_T = 250$ *ohms*. Note, also, that in a mixed group of parallel resistors, R_T is always smaller than the smallest resistor in the group.

Capacitors store energy

Capacitors collect electrical charges. That goes for *all* capacitors, whether they are made of plates, are electrolytics, are discaps, or tiny chips. All capacitors operate on the same principle so once you understand simple plate capacitors, you'll understand them all.

The capacitor in **Fig. 2A** is made of two parallel plates, each with surface area, A, and separated by distance, d. If you connect a battery or other voltage source across the capacitor, the voltage source forces electrons to flow from one plate to the other. (Remember, "like" particles repel each other and eventually the repulsive forces between the electrons will equal the force of the source trying to pack them into the plate. At that point, the voltage difference of the plates equals the source voltage.)

Now disconnect the voltage source. Because the packed electrons have no place to go, you have *stored energy*. When you place a load (such as a resistor) across the capacitor as in **Fig. 2B**, the electrons will follow that path trying to find a spot as far as possible from other electrons. This action occurs when you have the same number of electrons anywhere on either plate, as when you attached the voltage source; but in the meantime, while moving to equalize the charge, these electrons perform *work* in your load circuit.

The amount of charge you can store on a capacitor depends on the applied voltage and the geometry of the device; the term *capacitance* describes this geometry. And while you measure capacitance in *farads*, F, you'll see most component values in the less cumbersome form of μF (microfarads) or pF (picofarads).

For a parallel-plate capacitor,

$$C = 0.224 \frac{KA}{d} (n-1) \quad \textbf{(3)}$$

where

C = capacitance (pF)
K = dielectric constant of material between plates
A = area of one side of one plate (square inches)
d = separation of plate surfaces (inches)
n = number of plates

In **Equation 3** we have two physical constants, K and n. Constant K, is the dielectric

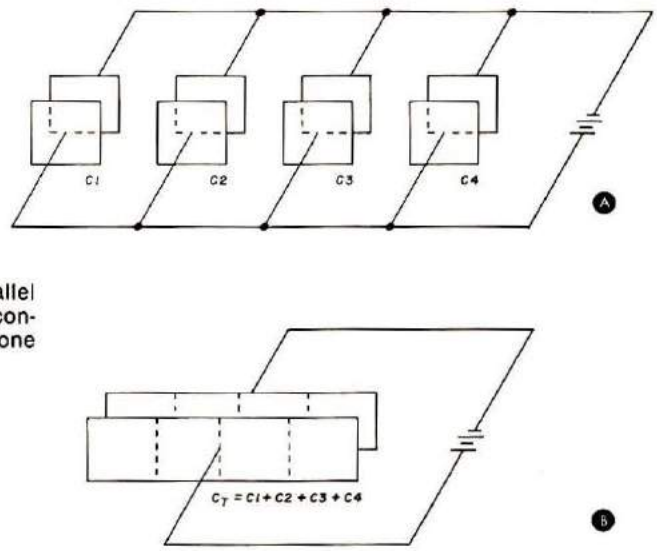


Fig. 3. Think of parallel capacitors **A** as disconnected sections of one larger capacitor, **B**.

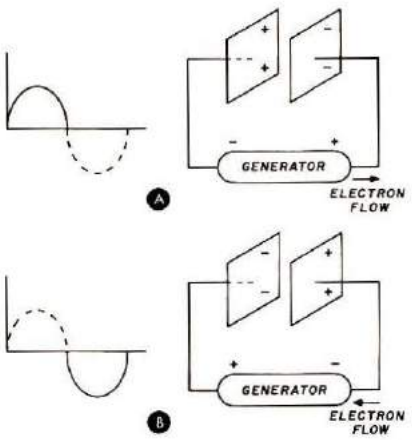


Fig. 5. Capacitors appear to pass ac by charging one plate during each positive half cycle **A**, and then by transferring that stored charge to the other plate for the negative half cycle, **B**, creating a current flow in the exchange.

constant of the insulating material used between the capacitor plates; for air, K is unity and physical materials such as glass, paper, mica, have Ks larger than one. The other constant in **Equation 3** is n, the number of plates in the capacitor.

If square centimeters are substituted for A and centimeters for d, then the factor 0.224 should be replaced with the factor 0.0882; all other terms remain the same.

Examination of **Equation 3** shows that increasing plate size or decreasing plate separation increases capacitance.

Make a dielectric sandwich

To keep the charges on the plates isolated, you have to separate the plates from each other with an insulator. Different insulators give any configuration different capacitances; K tells you how that capacitance compares with an air-filled device, whose K is one. Thus, with a value of $K = 1$ for air, if you fill a capacitor with mica ($K = 5.4$) you'll increase its capacitance by that same factor, 5.4. Thus, dielectrics let you buy higher capacitance components in smaller packages. The discussion above shows you how variable-plate capacitors work. As you turn the dial, you change the relative position of the plates from fully meshed (maximum C) to totally unmeshed (minimum C).

The concept of multiple-plate capacitors leads directly to the next point — how you add values of C in various arrangements. Suppose you have a number of plate capacitors connected as in **Fig. 3A**. Could you pretend they were all made of one big plate, as in **Fig. 3B**? Well, that's exactly right, because parallel capacitors merely sum their values to obtain the equivalent value (just as with series resistors).

Series capacitors **(Fig. 4A)**, like parallel resistors, are a little more tricky. Instead of increasing total C, the additional components make it more difficult to store charges and thus reduce the effective value according to the formula

$$C_S = \frac{1}{\frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3} + \ldots} \quad (4)$$

For example, suppose you need 2 μF but only have 4-μF caps on hand. Just connect two 4-μF caps in series to halve the effective value of either one.

It's easy to see, also, how

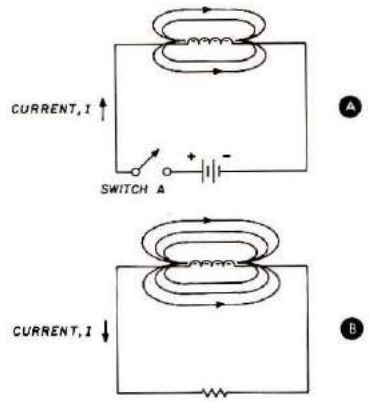


Fig. 6. The current that a voltage source pushes through an inductor builds up and maintains a magnetic field, **A**. But if you provide a path, as in **B**, the field will collapse, releasing its energy through the electrons it pushes through the circuit.

capacitors react to different frequencies. As you just learned, if you apply a dc voltage to a capacitor, the plates charge up and then current stops flowing. Thus capacitors block dc current. That certainly makes sense because in reality you've got a gap in the path — equal to the distance between the two plates. Any time you've got such a gap, you can't expect current to flow.

But, amazingly, even with this gap, capacitors do pass ac currents! In a typical ac signal's positive half-cycle **(Fig. 5A)**, the source moves electrons to one plate. When the source goes to zero and

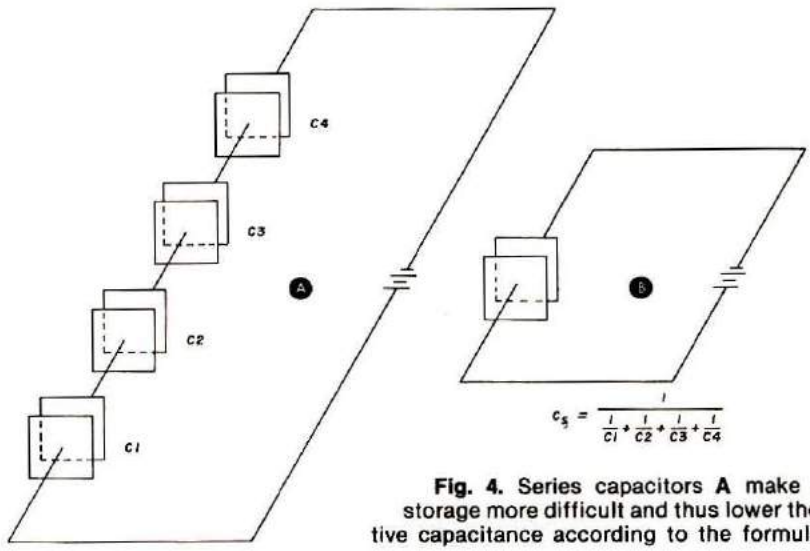


Fig. 4. Series capacitors **A** make charge storage more difficult and thus lower the effective capacitance according to the formula in **B**.

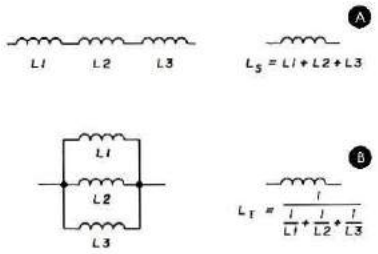


Fig. 7. Series inductors, **A**, and parallel inductors, **B**, both behave identically to their resistor counterparts.

then into its negative half-cycle (**Fig. 5B**), this stored-up charge moves to the other plate, and current flows back and forth as if it had a completed path. On the other hand, if the capacitor's plates weren't there, the source would have no place to store a charge and no current would flow at all. Thus, even though electrons do not actually flow through a *continuous* path through the capacitor, the circuit can't tell the difference.

Inductors play the field

In addition to capacitors, there's one other category of basic energy-storage devices you'll see quite often — inductors. To understand how they work, it's necessary to introduce two very simple concepts from physics: moving charges create magnetic fields, and a changing magnetic field likewise pushes charges around.

According to these laws, even a single wire carrying current sets up a magnetic field. That's true, but the resulting field is so small you can't depend on it to do anything useful. Instead, wind that wire into a coil, because that arrangement intensifies the magnetic field as much as any other; then you can put the field to work.

Just like capacitors, inductors (often called coils) store energy. For instance, when you throw switch **A** in **Fig. 6A**, current begins to flow. But remember, a moving charge creates a corresponding magnetic field. Just as you isolated your charged capacitor, disconnect the inductor's power source when the field has built up to its maximum intensity (**Fig. 6B**). The field stores energy because it wants to move electrons, but there's no place for the coil to release the electrons. If you connect a load resistor across the coil, the built-up energy begins to escape. This collapsing magnetic field induces a current flow through the load circuit.

The magnetic field that a coil can build depends on its geometry which is measured in *henrys* (H), *millihenrys* (MH) or *microhenrys* (μH). We can measure this *inductance* (L) with the formula

$$L = \frac{a^2 n^2}{9a + 10b} \qquad (5)$$

where

L = inductance (μH)
a = coil radius (inches)
b = coil length (inches)
n = total number of turns

If a and b are in centimeters, **Equation 5** becomes:

$$L = \frac{0.16a^2 n^2}{3.5a + 3.9b} \qquad (6)$$

Thus, while coil radius can either increase or decrease coil inductance, increasing the number of turns for a given length increases L; while increasing the length for a certain number of turns will decrease L. The ratio of coil length, b, to coil diameter $(2a)$ is called the form factor, which is important in many designs using inductances.

You should easily recognize what happens when you connect inductors in series — it's just like piecing one longer coil together (**Fig. 7A**), adding all the turns. Thus, you can merely sum their individual values together, as with series resistors. As with parallel resistors, you'll have to use the trickier formula for parallel inductors, as shown in **Fig. 7B**.

Changes mean more work

Remember how capacitors block dc and pass ac signals? Inductors do just the opposite — they pass dc and inhibit ac. You just saw how dc sets up a magnetic field in a coil. But once the dc builds up the field to its maximum value, the current passes through the coil unimpeded without doing any additional work, because only *changing* currents set up these fields. (When you turn on the current, you change its value for a brief instant, right? That's when the field builds up. The continuous current flow merely maintains that field.)

However, if you place an ac source across the coil, the current changes constantly from positive to negative. The current is so busy in the coil building up a field in one direction and then, when it changes polarity, building up another field in the other direction, that it has a tough time getting through the coil to do any useful work. Now you can see how inductors inhibit ac signals while passing dc.

There's one additional effect to become familiar with: *mutual inductance*. If you align two coils properly and build up a field in one, that field extends into the field of the other coil

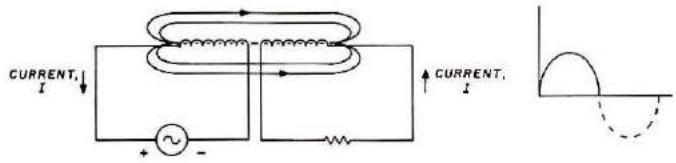


Fig. 8. This field couples, or connects, the two inductors, so that a current flowing in the left-hand circuit produces a proportional current in the right-hand circuit.

as well **(Fig. 8)**. Remember that a changing magnetic field pushes electrons; so moving electrons in one coil with a current will induce a field that couples the two coils. Thus a current in the second coil occurs without any physical interconnection. Transformers, in particular, rely on this effect.

Put the pieces together

Now you'll see that you can connect these various components — resistors, capacitors, and inductors — in various ways to work with different frequencies. (How to make these connections, however, is the topic of other articles.) For now, you've mastered a very important lesson: different components let you select different frequencies for whatever purposes you wish.

Bibliography

1. David Halliday and Robert Resnick, *Physics*, Part II, John Wiley & Sons, Inc., New York, 1962.
2. Sy Levine, *Electronic Business Magazine's Basic Electronics Course — From Ohm's Law to Microprocessors*, Cahners Publishing Co., Boston, 1976.
3. *The Radio Amateur's Handbook*, American Radio Relay League, Newington, Connecticut, 1977.

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